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From Simple to Super- and Ultra-Complex Systems: A Paradigm Shift Towards Non-Abelian Emergent System Dynamics

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1. Introduction

So far, the development of system theory has been remarkably uneven: phases of tumultuous development arousing vivid expectations have been followed by periods of stagnation if not utter regression. Moreover, within the different sciences, the theory of systems is customarily seen and presented in rather different ways. The differences are often so remarkable that one may ask whether there is in fact anything like "the" theory of systems. Thirdly, it is worth mentioning that more often than not a number of conceptual confusions continue to pester the development of system theory. Remarkably enough, during the past few decades systems theory has reproduced in its own way the same divide and the same attitude that has characterized recent mainstream philosophy, namely the overwhelming prevalence assigned to the epistemological interpretation to their object as opposed to the ontologically-oriented analysis of their object. According to the epistemological reading, system's boundaries are in the eye of the observer; it is the observer that literally creates the system by establishing her windowing of attention. On the other hand, the ontological reading claims that the systems under observation are essentially independent from the observer, which eventually discover, or observe, them. Most confusions can be dealt with by distinguishing two aspects of the *interactions between observing and observed systems*. The thesis that knowing a system, as required e.g. by any scientific development, implies appropriate interactions between an observing and an observed system, does not mean that existence or the nature of the observed system depends on the observing system, notwithstanding the significant perturbations introduced by measurements on microscopic, observed quantum systems.[1] A measuring device can be taken as one among the simplest types of observing systems (Rosen, 1968a; 1991; 2000). The resulting *model* depends essentially on the device (e.g., on its sensitivity and discriminatory capacity); on the other hand, the nature of the observed system does not depend on the nature of the measuring device (which obviously shouldn't exclude the possibility that the very process of measuring may eventually modify the observed system). Furthermore, the ontological interpretation helps in better understanding that some systems essentially depend on other systems in either a *constructive* (Baianu, 1973; Baianu and Marinescu, 1974 or an *intrinsic* (Baianu et al, 2006a,b), sense; whereas the constructive dependence occurs because of the logical and/or categorical process underlying the emergence of the higher level structure of the whole system from its key component subsystems, the intrinsic dependence may occur for example as a result of the immanent, many-valued logic of highly complex systems (Baianu, 1977; 1987-2006). Thus, higher-order systems require at least first-order systems as their constitutive elements, the basic idea being that higher-order systems result from the couplings among other, lower-order systems. In this sense, melodies require notes, groups require agents and traffic jams involve cars. The two types of dependence need not exclude each other and one may also encounter both types in highly complex systems.

This paper is divided in two main parts. The first part (Sections 2 to 4) serve as an introduction to general system theory. Our aim is to present the evolution of system theory from a categorial viewpoint; subsequently (sections 5 to 8) we shall study systems from the standpoint of an

[1] Needless to say, both systems – in the case of a two-systems coupling, can be observing. Furthermore, the observing system can observe itself, or parts (subsystems) of itself.

'universal' Topos, logico-mathematical, constructions that cover both the *commutative* and the *non-commutative* frameworks. In so doing, we shall distinguish three major phases in the development of the theory (two already completed and one in front of us). The three phases will be respectively called "*The Age of Equilibrium*", "*The Age of Complexity*" and "*The Age of Super-complexity*". The first two may be taken as lasting from approximately 1850 to 1960, and the third being rapidly developed from the 1940s (Eilenberg and Mac Lane, 1945) and the late 1950s and 60s (Rashevsky, 1954, 1967-1969; Rosen, 1958a, b). Each phase is characterized by reference to distinct concepts of the 'general' system, meant in each case to include all possible cases of specific, actual systems, but clearly unable to do so as the paradigm shifts from simple to 'complex', and then again to extremely complex or *super-complex* (previously called 'ultra-complex'; Baianu, 2006; Baianu et al., 2006 a, b) classes of systems. Furthermore, each subsequent phase generalized the previous one, thus addressing previously neglected, major problems and aspects, as well as involving new paradigms. The second part deals with the deeper problems of providing a flexible enough mathematical framework that might be suitable for various classes of systems ranging from simple to super-complex. As we shall see, this is something still in wait as mathematics itself is undergoing development from 'symmetric' (commutative, or 'natural') categories to dynamic 'asymmetry', or non-Abelian constructs and theories that are more general and less restrictive than any static modelling.

2. The Age of Equilibrium

The first phase in the evolution of the theory of systems depends heavily upon ideas developed within organic chemistry; '*homeostasis*' in particular is the guiding idea: A system is a dynamical whole able to maintain its working conditions. The relevant concept of system is spelt out in detail by the following, general definition, D1.

D1. A system is given by a bounded, but not necessarily closed, category, or super-category, of stable, interacting components with inputs and outputs from the system's environment.

To define a system we therefore need (1) *components,* (2) mutual interactions or links; (3) a separation of the selected system by some *boundary* which distinguishes the system from its environment; (4) the specification of system's environment; (5) the specification of system's categorical structure and dynamics; (6) a super-category will be required when either components or subsystems need be themselves considered as represented by a category, i.e. the system is in fact a super-system of (sub) systems, as it is the case of emergent super-complex systems.

Point (5) claims that a system should last for a while: a system that comes into birth and dies off 'immediately' has little scientific relevance as a system,[2] although it may have significant effects as in the case of 'virtual particles', 'photons', etc. in physics (quantum electrodynamics and chromodynamics). Note also that there are many other, different mathematical definitions of 'systems' ranging from (systems of) coupled differential equations to operator formulations, semigroups, monoids, topological groupoids and categories that represent a formal rather than an ontological view of general systems. Clearly, the more useful formal system definitions include *algebraic and/or topological structures* rather than simple sets (discrete topological structures) or their categories (Baianu, 1970; Baianu et al, 2006). The main intuition behind this first understanding of dynamic systems is well expressed by the following passage: "The most general and fundamental property of a system is the interdependence of parts or variables. Interdependence consists in the existence of determinate relationships among the parts or variables as contrasted with

[2] Claim (5) can be included under (2) by reformulating it as "repeated mutual interactions".

randomness of variability. In other words, interdependence is *order* in the relationship among the components which enter into a system. This order must have a tendency to self-maintenance, which is very generally expressed in the concept of equilibrium. It need not, however, be a static self-maintenance or a stable equilibrium. It may be an ordered process of change – a process following a determinate pattern rather than random variability relative to the starting point. This is called a moving equilibrium and is well exemplified by growth" (Parsons 1951, p. 107).

2.1 Selective Membranes, Boundaries and Horizons

Boundaries are peculiarly relevant to systems. They serve to distinguish what is internal to the system from what is external to it. By virtue of possessing boundaries, a system is an entity for which there is an interior and an exterior defined for such an entity. The initial datum, therefore, is that of a difference, of something which enables a (characteristic or essential) difference to be established between a system and its environment.

An essential feature of boundaries of *open* systems is that they can be crossed. There are more open boundaries and less open ones, but they can all be crossed. On the contrary, a horizon is something that we cannot reach or cross. In other words, *a horizon is not a boundary*. As far as systems are concerned, the difference between inside and outside loses its common sense, 'spatial' understanding. As a matter of fact, 'inside' doesn't anymore mean 'being placed within', but it means 'being part of' the system. One of the earlier forerunners of system theory clarified the situation in the following way: "Bacteria in the organism ... represent complexes which are, in the organizational sense, not 'internal', but external to it, because they do not belong to the system of its organizational connections. And those parts of the system which go out of its organizational connections, though spatially located inside it, should also be considered as being ... external." (Bogdanov 1984, p. 81). In other words, internal and external are first and foremost relative to the system, not to its location within physical space. The situation is, however, less clear-cut in the case of viruses that insert themselves into the host genome and are *expressed* by the latter as if the viral genes 'belonged' to the host genome. Even though the host may not recognize the viral genes as 'foreign', or 'external' to the host, their actions may become incompatible with the host organization as in the case of certain oncogenic viruses that cause the death of their host. An even less obvious 'externalization' occurs in the case of malignant cancer cells that are derived through neoplastic transformations from normal cells that originally were indistinguishable from their neighbours in terms of their being part of the internal organization of the original multi--cellular organism. The fact that some systems are able to enslave other systems or to exploit them might thus be treated as a form of 'parasitism' – which is a one-way relation as it benefits only the 'parasite' organism at the expense of the host – if such systems were not actually really internal to the host; in such complex, special cases the 'internality', or 'externality' is defined only by the dynamic compatibility of the intruder relative to that of the host organism; this compatibility can thus be described in terms of competing – or conflicting – attractors of the host and intruder, respectively. Let us add that internal and external can also be taken as features describing the difference between the world of 'inanimate' things/machines and the world of organisms. In the mechanistic, 'linear' order of things or processes, the world is regarded as being made, or constituted, of entities which are *outside of each other*, in the sense that they exist independently in different regions of space (and time) and interact through forces. By contrast, in a *living* organism, each part grows in the context of the whole, so that it does not exist independently, nor can it be said that it merely 'interacts' with the others, without itself being essentially affected in this relationship. The parts of an organism grow and develop together. Unfortunately, this is also true of the malignant tumours that grow at the expense of the 'host' (diseased) organism.

As soon as a boundary is established, both separating and connecting the system to its environment, a second type of boundary may arise, namely the one distinguishing the centre of the system from its periphery (the former boundary will be termed 'external' boundary, and the latter 'internal'). The centre, once established assumes control over the system's external boundary and can modify the boundary's behaviour. Multi-modal systems may require a multiplicity of centres, for each of the relevant modalities. When different centres are active, a secondary induced dynamic arises among them.

Boundaries may be clear-cut, precise, rigid, or they may be vague, blurred, mobile, or again they may be intermediate between these two typical cases, according to how the differentiation is structured.

The usual dynamics is as follows. It begins with either vague, random oscillations or an original asymmetry. These introduce differences among the diverse areas of a developing, or growing, region. The formation of borderline phenomena (such as surface tension, pressure, competition) only occurs later, provided that the differences prove to be sufficiently significant. Even later there arises a centre, or a node, whose function is primarily to maintain the boundaries.

Generally speaking, a closed boundary generates an internal situation characterized by limited differentiation. The interior is highly homogeneous and it is distinct from whatever lies outside. Hence, it follows that whatever lies externally is inevitably viewed as different, inferior, inimical; in short, as something to be kept at a distance. A second consequence of closed boundaries is the polarization of the *internal* space of the system into a *centre* and a *periphery*. The extent of this problem was already noted by Spencer, who accounted for it with his law of the concentration of matter-energy. Open boundaries allow instead, and indeed encourage, greater internal differentiation, and therefore, a greater degree development of the system than would occur in the presence of closed boundaries. In its turn, a population with marked internal differentiation, that is, with a higher degree of development, in addition to having numerous internal boundaries is also surrounded by a nebula of functional and *non-coincident* boundaries.

This *non-coincidence* is precisely one of the principal reasons for the dynamics of the system. However, note that in certain, 'chaotic' systems organized patterns of spatial boundaries do indeed occur, albeit established as a direct consequence of their 'chaotic' dynamics. This *non-coincidence* is precisely one of the principal reasons for the dynamics of the system. Efforts to harmonise, coordinate or integrate boundaries, whether political, administrative, military, economic, touristic, or otherwise, generate a dynamic which constantly re-equilibrates the boundary situation. In certain, 'chaotic' systems organized patterns of spatial boundaries occur as a direct consequence of their 'chaotic' dynamics. In these cases, the border area becomes highly active, and it is in this sense that we may interpret the remark by Ludwig von Bertalanffy that "ultimately, all boundaries are *dynamic* rather than spatial" (Bertalanffy 1972, p. 37).

Corresponding to such a logic of boundaries is a more or less *correlative logic of centres*. If to every boundary there corresponds a centre responsible for its maintenance, the dynamics of boundaries reverberates in a corresponding dynamics of centres. The multiplicity of boundaries, and the dynamics that derive from it, generate interesting phenomena. Campbell was the first to point out that boundaries tend to reinforce one another (Campbell 1958). We quote Platt on the matter: "The boundary-surface for one property ... will tend to coincide with the boundary surfaces for many other properties ... because the surfaces are *mutually-reinforcing*. I think that this somewhat astonishing regularity of nature has not been sufficiently emphasized in perception-philosophy. It is this that makes it useful and possible for us to identify sharply-defined regions of space as 'objects'. This is what makes a collection of properties a 'thing' rather than a smear of overlapping images;

any violation of boundary-coincidence has an upsetting fascination for us, as in tales of ghosts, which can be seen but not touched" (Platt 1969, p. 203).

The following synopsis (modified from Poli, 2001b) summarizes the main structural features of system boundaries:

- nature (external/internal)
- structure (gates, filters, selective, overlaps, connectivity, intrinsic or functional organization)
- cardinality (as a single boundary or as a border area)
- dynamics (changes in location, boundary exchange, variable topology with time)
- form (open/closed, mobile/static, flexible/rigid)
- maintenance (integrity, growth, destruction);

To these features, the so-called *law of transposition* should be added: a characteristic of *all* structures with an emerging structure at a higher level is that its boundaries can be revealed by transposition.

The analysis set out in this section has been conducted with the deliberate omission of any reference to levels of reality (Poli 2001a, 2006, 2007, 2008). The inclusion of explicit consideration of the problem of stratification into levels will be shown to significantly increase complexity thus leading to 'super--complexity', as explained in Section 4 below).

3. The Age of Physical 'Complexity', Computers and Chaotic Dynamics

After the Second World War, cybernetics, game theory, information theory, computer science, general systems theory, and other related fields flourished. Subsequently, there was also the first report of a categorical approach to complex biological systems which is Robert Rosen's seminal paper on the metabolic-replication, (**M,R**)-systems and the general, abstract representation of biological systems in the category of sets (Rosen, 1958a,b), in a purely functional, or organizational sense.

The main result achieved by the first phase of development of system theory has been the proof that the system as a whole is defined by properties *not pertaining to any of its parts* – a patently *non-reductionist* view. Global equilibrium (multi-stability, etc) are all properties of the whole systems, not of their parts. However, much more than this is required to understand system dynamics. The simplest way to see what is lacking runs as follows. According to some system theories, a system *is the whole* resulting from the interactions among its components. There are at least three hidden assumptions embedded in this definition. The first assumption is that all the components are given in advance, before the constitution of the system, or that they might be distinguished through some canonical decomposition (as in the case of sequential machines or automata). We shall discuss this problem under the heading of the system's *constitution*. The second assumption becomes apparent as soon as one asks what happens when components change: What happens when a component is no longer part of the system, or it fails? What happens when a new component enters the system or is generated internally? What happens when elements die out? These groups of questions can be summarized as the problem of the `*reproduction'* of the system, i.e. as the problem of the `historical' continuity of the system through time—though not in either a topological or strict dynamical sense—as distinguished and opposed to the continuity of its components, in the same historical sense. The third hidden assumption is that all the changes are placed on the side of the environment. What about systems that are able to learn and to develop new strategies for better dealing with survival or other problems they may run into? Systems endowed with this property will be called *adaptive*.

3.1 The Constitution, Reproduction and Adaptability of Systems

Two forms of constitution should be distinguished: *the bottom-up* type of constitution from components of the system (that are already available), and *the top-down* constitution from (a previous stage of) the system into its components. This latter form of constitution comes in two guises: (1) as constraints on initial conditions and the phase space of the system components, and (2) as the creation of new elements, i.e. the development of a new organizational layer, or layers, of the system.

3.1.1. Adaptive and Autopoietic Systems in Relation to *Dynamic Genericity*

We shall discuss first how and why adaptive systems possess or exhibit dynamic genericity and autopoiesis.

All adaptive systems seem to require at least two layers of organization: the first layer of the rules governing the interactions of the system with its environment and with other systems, and a higher-order layer that can change such rules of interaction; the changes that occur may be purely casual, or may follow pre-established, or acquired, patterns. In this regard, a hypothesis can be advanced which claims that the main difference between non-living natural systems on the one hand, and living natural systems, psychological systems and social systems on the other, is that the former present only one single organizational layer of interactions; the latter, more complex systems present at least two layers of organization: the one governing interactions and the one capable of modifying the rules of interaction. The persistence in time of the latter systems that are highly complex is made possible by dynamic *multi-stability* (Baianu, 1970) – a source of their state-space, or state-*genericity* – a form of structural/dynamic/topological stability to perturbations that prevents the destabilization and rapid disappearance of such systems. Genericity replaces in highly complex systems the degeneracy characteristic of simple, physical systems with strictly deterministic causality and dynamics represented by systems of ordinary, or partial, differential equations. Genericity, multi-stability/homeostasis and autopoiesis may also be related to symmetry breaking or repeated symmetry breaking, as discussed next in further detail.

3.2. System Reproduction, Regeneration, Repair and Logic Entailments. Asymmetry Roles in Growth and Development

Autopoiesis (or *regeneration*) was previously defined as *the capacity of a complex system to generate the components of which it is composed*. The simplest mathematical models mimicking such 'biological' capabilities are arguably Robert Rosen's (**M,R**)-systems (Rosen, 1958a,b). Their categorical construction from component objects and maps, using natural transformations and the fundamental Yoneda-Grothendieck Lemma (Baianu and Marinescu, 1974) elicits their implicit algebraic structures, and furthermore allows their possible extension to more general categories and structures than Rosen's (**M,R**)-systems in the categories of sets, such as, the cartesian closed categories of generalized, algebraic (**M,R**)-systems (Baianu, 1973). Complex, molecular dynamic representations of both (**M,R**)-systems (Rosen, 1971, 1973, 2000) and Rashevsky's organismic sets (1964-1969) have also been constructed in terms of natural transformations of molecular biology systems (Baianu, 1980, 1984, 1987a,b; Baianu et al., 2005--2007 a--c). Such categorical, multi-level constructs of generalized, algebraic metabolic-repair/regenerating systems illustrate the *hierarchical layers* occurring in super-complex biological systems that will be further discussed here in Section 4.

3.2.1 Asymmetry Roles in Cell Division, Organismic Growth and Development, Human Brain Functions and Mental Processes

An original asymmetry at the beginning of growth, following the fertilization of an ovum, seems to play an important role in determining the preferred growth axis (or axes); it seems also to be responsible for introducing constraints in the potentially possible variable topologies during embryogenesis/organismic development. Furthermore, the structural/anatomical asymmetry of the human brain between its left and right hemispheres, and also extends apparently to the mental `functions' correlated or supported at least in part by such hemispheres. Interestingly, the human brain appears to be rather *unique* in regard of its asymmetric structure(s).

3.3 Complexity as an Intrinsic Organizational Property. Structural Symmetry and Dynamic Symmetry Breaking

The overall outcome of constitution, reproduction and autonomy is *complexity*. The guiding connection changes from the system-environment connection to the connection between the system and its complexity. Not by chance, *self-referential* phenomena and systems have started to receive substantial attention. Summing up, complex systems are *adaptive* systems capable of regeneration making 'copies' of themselves by reproducing the elements they are made of through a 'fission-like' process of cell division, followed by topological/structural and organizational/functional transformations. As far as self-referential systems are concerned, the guiding relation is no longer the 'system ↔ environment' opposition or duality, but the 'system ↔ system' intra-relations, or automorphisms. Ultimately, the difference between *openness* and *closure* acquires a different meaning: now *openness* means exchange with the environment, whereas *closure* generates structure, a key attribute of the system which provides its identity by organizing the system as an integral whole, or a *holon*. The closure should not be however misunderstood in the sense of major restrictions placed on the system's exchanges with the environment.

3.4. From Structural Symmetry to Dynamic Symmetry Breaking: Increasing both Complexity and Genericity during Higher Level Emergence

A recognized path for the emergence of higher dynamical complexity levels is provided by dynamic symmetry breaking. The role of structural symmetry and dynamic symmetry breaking in changing levels and causing the emergence of increasing complexity levels can be further considered as shown in the following diagram (**Figure 3.4.1**):

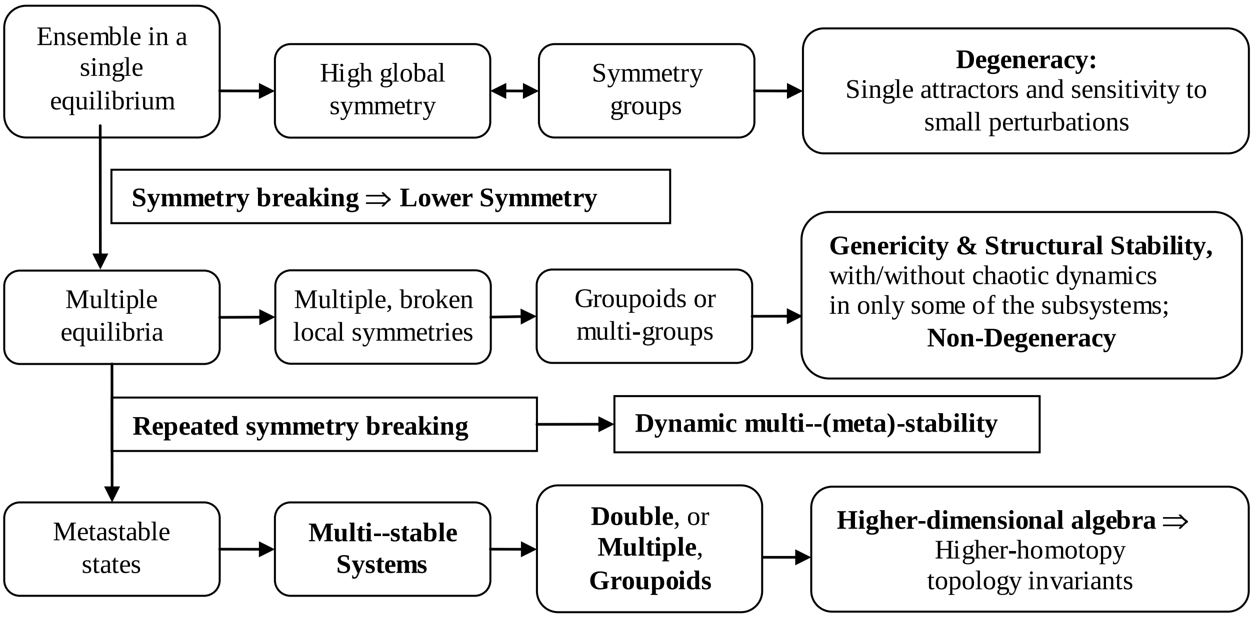

Figure 3.4.1. The roles of symmetry breaking and the corresponding groupoids structures in the emergence of higher complexity levels of reality: repeated symmetry breaking leads at first to double groupoids, and then to multiple-groupoids in a higher dimensional algebra of highly complex dynamics characterized by multi-stability and genericity of states in super-complex (organismic) systems. The 'living' states thus formed are both meta-stable and generic, achieving structural stability or 'resistance' to external perturbations, unlike chaotically-complex systems that are neither generic nor meta-stable.

The following provides a more detailed explanation of the interesting properties derived from such emergence phenomena.
The super-complex systems that have thus emerged exhibit several properties considered essential to life and its maintenance/propagation: autopoiesis, self-repair capabilities (as for example in (M-R) system models), and self-reproduction or sexual reproduction capability. Such highly complex systems also comprise logically heterogeneous classes that can be properly understood only in terms of their operating n-valued, LM-logics underlying their genetic networks/active genomes (Baianu, 1977; Baianu et al, 2006a,b; 2007a, 2008).

Obviously, not all initial, quantum/ multi-- molecular systems are capable of emerging in this fashion through repeated symmetry breaking. One of the major tasks of any complete super-complexity theory is therefore to identify the *initial* conditions and quantum/ molecular components that must exist for the *super-complexity emergence* to occur starting from certain, either chaotic or quantum, systems; the latter seems the more likely class of candidates as quantum dynamics appears to 'quench' chaotic dynamics and the extreme sensitivity to perturbations that chaotic-complex systems exhibit. A related, interesting but open question is if the emergence of the ultra-complex, *meta-level* of the human mind also involves repeated symmetry breaking and the corresponding, multiple-groupoid structures with their non-Abelian higher dimensional algebra. Considerations made elsewhere would seem to indicate that this is indeed the case, but additional conditions for the interactions among super-complex systems are also necessary for the emergence of the *uniquely ultra-complex* human mind (Baianu et al., 2007a); emergent dynamic features such as meta-stable, generic states and multi-stability are, however, likely to recur at the meta-level of the human mind (see also for example, Baianu, 1970, 1971a ,b; Baianu et al, 2008).

4. The Age of Super-Complexity (1968 ⇒). Strata and Layers of Reality: Emergence through Interactions. Chronotopoids and Anticipation

Living systems (including among living systems not only biological systems but psychological and social systems as well) present features remarkably different from those characterizing non-living systems. We propose that super-complexity requires at least four different categorical frameworks, namely those provided by the theories of levels of reality, chronotopoids, (generalized) interactions, and anticipation. Furthermore, the claim is defended that novel logical frameworks (Baianu et al, 2007a) as well as a new conceptual/mathematical framework is required (Brown et al, 2007; Baianu et al, 2007a).

4.1 Strata of Reality

The distinction is widespread among three basic realms or regions (or strata, as we will call them) of reality. Even if the boundaries between them are differently placed, the distinction among the three realms of material, mental and social phenomena is essentially accepted by most thinkers and scientists. A major source of discussion is whether inanimate and animate beings should be placed in two different realms (this meaning that there are in fact four and not three realms) or within the same realm.

From a categorial point of view, the problem about how many strata there are can be easily solved. Leaving apart universal categories (those that apply everywhere), two main categorial situations can be distinguished: (a) Types (Items) A and B are categorially different because the description (codification or modelling) of one of them requires categories that are not needed by the description (codification or modelling) of the other; (b) Types (Items) A and B are categorially different because their description (codification or modelling) requires two entirely different groups of categories. We term the two relations respectively as relations of over-forming and building-above (Hartmann 1935). Strata or realm of reality are connected by building-above relations. That is to say, the main reason for distinguishing as clearly as possible the different strata of reality is that any of them is characterized by the birth of a *new* categorial *series*. The group of categories that are needed for analyzing the phenomena of the psychological stratum is essentially different from the group of categories needed for analyzing the social one, which in its turn requires a group of categories different from the one needed for analyzing the material stratum of reality.

Over-forming (the type (a) form of categorial dependence) is weaker than building-above and it is used for analyzing the internal organization of strata (together with building-above and eventually other types of relation). Each of the three strata of reality has its specific structure. The case of the material stratum is the best known and the least problematic. Suffice it to consider the series atom-molecule-cell-organism (which can be extended at each of its two extremes to include sub-atomic particles and ecological communities, and also internally, as needed). Compared to the material realm, the psychological and social ones are characterized by an interruption in the material categorical series and by the onset of new ones (relative to the psychological and social items). More complex types of over-forming are instantiated by them.

The next step is to articulate the internal organization of each stratum (see Poli 2001a, 2006, 2007 for more details).

4.2. Levels and Meta—Levels of Reality.

Terminological considerations are here essential: Poli (2001a, 2008) uses the term `level' to refer in general to the levels of reality, restricting the term `stratum' to *building-above* relationships and the term `layer' to *over-forming* relationships, and we shall eventually use the expressions `sub--layer' and `sub--stratum' when analysis will require them. On the other hand, a meta—level is a term that emerged from the logical and mathematical analysis of categories of categories; to resolve antinomies in the mathematical theory of sets, such as ``the set of all sets is not a set", the term class has been reserved for ensembles containing sets. Thus, a class is a type of `meta—level' of sets, and their existence still relies on the membership relation, that is, `an element belongs to a set'. In category theory, a `category' of categories is, in fact, a `meta--category' or super-category (Mitchell, 1968; Mac Lane, 2000). In both cases, that of a class and a super--category, one has in fact three levels: the 0^{th} level is that of elements or objects, that belong respectively to sets or categories, the first level of sets or categories, and then the second level, or meta--level, of respectively classes and 2--categories (super--categories or meta—categories). Furthermore, the links, or morphisms (arrows) between objects have distinct actions and properties at the meta-level from those of the `lower' levels; 2-level morphisms are functors between categories, and 3-level morphisms are natural transformations of functors. Neither functors nor natural transformations (or `functorial morphisms') can be regarded as mere mappings; in fact, the meta-level morphisms – natural transformations—are where most of the interesting action is in Category Theory, which is thus intrinsically meta—theoretical in character. The attribute `natural' of `functorial morphisms' also reflects their intrinsic type of symmetry/property, called *commutativity* which is present in the square diagrams that define them and that are `natural' (see for example, Mitchell, 1968, Popescu, 1973 or Mac Lane, 2000 for the rigorous definition of functorial morphisms involving such `natural', square diagrams.) In actual use, the term *meta* is employed in Category Theory for *meta--theorems* that emerge in a similar form from the first to the second level (2-category or super-category). Notably, the meta—levels do not stop at the second level discussed here, but can go up higher to the n—th level, with **n** being an integer. Thus, an n—category is still a meta—level category of a higher order, and thus belongs to Higher Dimensional Algebra (Brown et al 2007a, b). One also notes that this feature of Category Theory and Higher Dimensional Algebra is very attractive both as a logically-consistent tool and as a framework for a relational approach to highly complex systems and their dynamics (Baianu and Marinescu, 1969; Baianu, 1970-1973, 1987-2008; Baianu et al, 2007a—c). In the case of biological organisms—which are super-complex dynamic systems (cf. Baianu et al, 2007a, 2008), their meta--level was represented by `Organismic Supercategories' (OS) that required a special axiomatics (ETAS, in Baianu, 1970). Similar considerations were made in Relational Biology by Nicolas Rashevsky (1969) who considered both living organisms and human societies as `Organismic Sets' even though such sets have only a discrete topology and no explicit connectivity, organizational structure or links. It was only recently shown (Baianu et al., 2007a, 2008) that the super-complexity level of organisms has emerged/emerges as a direct consequence of their internal dynamics and ontogenetic development. In Rashevsky's theory of organismic sets the 0^{th} level is that of the genes (it was thus conceived as a biomolecular level), whereas living cells of a multi-cellular organism were considered to form the first organizational levels, and then the multi-cellular, organismic level would constitute the second organizational level. One notes here also that the multi-cellular, organismic level of eukaryotes satisfies the three--level criterion for the existence of a meta—level, that of the super-complex dynamic system of the eukaryotes, but that prokaryotic organisms like bacteria would not meet the three--level requirement for a meta—level. In the case of human societies, the three-level criterion can always be met, the suggested levels involved being the human organism, the mind and the human society (Baianu et al, 2007a, 2008) with the additional proviso that the human mind can be ` in itself' considered as a meta—level of existence, above those of the living human organism and cells, or genes/ biomolecules. Thus, atoms, molecules, organisms distinguish levels of reality because of the causal links that govern their behaviour, both horizontally (atom-atom, molecule-molecule, organism-organism) and vertically (atom-molecule-organism). This is a first intuition of the theory of levels. Even if the further development of the theory requires imposing a number of qualifications to this initial intuition—such as existence of meta—levels in the sense introduced here-- the idea of a series of entities organized on different levels of complexity will prove correct. Briefly, the difference between levels of reality and levels of interpretation requires acknowledging that the *items* composing levels of reality are endowed with their own form of *agency* (Poli 2007, 2008). *Mutatis mutandi,* the same kind of reasoning holds for meta—levels. Thus, the molecular level –which is extremely rich in the number of different types of molecules—more so than its sub—level of atoms, can be considered as a meta—level of electrons and stable nucleons (protons and neutrons), because the latter are thought to be `made of ' up (*u*) and down (*d*) quarks; thus, the mathematical requirement of a meta—level for the existence of three consecutive levels is satisfied in the case of the molecular meta—level of the quarks and electrons, albeit by intertwining the 0^{th} and first level. On the other hand, if the electrons were to be found to have also a `quark—like' substructure, then the three-level requirement for the molecular meta—level would be exactly satisfied, without any level intertwining. One notes however that the use of the term meta—level in Logics and Mathematics is more restrictive and more sharply defined than the flexible and broader meaning that we propose to employ here in the ontological theory of levels (and also `meta—levels'); therefore, one could avoid potential semantic confusions by referring precisely to the latter meta concept as *ontic meta—levels.*

Most details of the links connecting together the various levels of reality are still unknown, because the various sciences had mainly been working on causal links *internal* to their regional phenomena. The lack of a theory of levels of reality has been the major obstruction to the development of the needed theories. Proposal concerning the architecture of levels and their links will improve our understanding of the world and its many dependences.

The deepest access to the ontological theory of levels is achieved by adopting a categorical viewpoint. In short, a level of reality is represented by a group of (ontological) categories (Poli 2008). The next step is to distinguish *universal* categories, those that pertain to the whole of reality, from *level* categories, those that pertain to one or more levels, but not to all of them. The question now arises about how the material, psychological and social strata are connected together. The proposal defended in Poli (2001a) and subsequent papers is that material phenomena act as bearers of *both* psychological *and* social phenomena. In their turn, psychological and social phenomena reciprocally determine each other. Psychological and social systems are formed through co-evolution, meaning that the one is the environmental prerequisite for the other (Luhmann, 1995).

4.3. Chronotopoids

The theory of levels paves the way towards the claim that there could be *different* families of times and spaces, each with its own structure. We shall argue that there are numerous types of real times and spaces endowed with structures that may differ greatly from each other. The qualifier "real" is mandatory, since the problem is not the trivial one that different abstract theories of space and time can eventually be and have been constructed (Poli, 2007, 2008). We shall treat the general problem of space and time as a problem of *chronotopoids* (understood jointly, or separated into *chronoids* and *topoids*).[3] The guiding intuition is that each stratum of reality comes equipped with its own family of chronotopoids (see Poli, 2007 for further details).

4.4. Interactions

The theory of levels of reality provides as well the natural framework for developing a full-fledged theory of causal dependences (interactions). As for the case of chronotopoids, levels support the hypothesis that any level has its own form of causality/ interaction (or family of forms of causality/interaction). Material, psychological and social forms of causality/interaction could therefore be distinguished (and compared) in a principled way. Beside the usual kinds of basic causality between phenomena of the same nature, the theory of levels enables us to distinguish upward and downward forms of causality/interaction (from the lower level to the upper one and *vice versa*). This acknowledgement provides the needed context for distinguishing material, psychological and social types of interactions.

4.5 Anticipation

An Anticipatory System is a system such that the choice of the action to perform depends from the system's anticipations of the evolution of itself and/or the environment in which it is placed (Rosen, 1985). Reactive systems, on the contrary, are such that subsequent states depends entirely from preceding states (usually, according to some law or rule). Anticipation comes in different guises: the simplest distinction is between strong and weak types of anticipation, where the former (the strong one) is meant as coupling between the system and its environment, while the latter (the weak one) is understood in the form of a (cognitive) model developed by the anticipatory system itself. As a straightforward consequence, evolutionary survival implies that all living systems are characterized by some form of another of strong anticipation, while some among the most evolved species may enjoy weak types of anticipation as well.

Anticipation can therefore lie low and work below the threshold of consciousness or it may emerge into conscious purpose. In the latter form it constitutes the distinctive quality of causation within the psychological and the social realms. On the other hand, biological systems are better characterized by non-representative (model-based) types of anticipation.

Complexity, as usually – and most likely incorrectly understood – is entirely past-governed and apparently does seem to be unable to include anticipatory behaviour. In order to distinguish anticipatory systems from entirely past-governed systems, the concept of *super-complexity* has been recently introduced (see Baianu 2006, special issue of *Axiomathes* dedicated to Robert Rosen; also with precise definitions and specifications by Baianu et al, 2007a,b).

A different but not opposite way to understand anticipation is to see the theory of anticipatory systems as providing a *phenomenological*, or first-person, type of description, while most of complexity theory is usually based on third-person descriptions. The theory of anticipatory systems can therefore be seen as comprising both first- and third-person information. The interactions between the two types of descriptions may result in many cases in a substantial reduction of the state space characterizing the dynamics of anticipatory systems.

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[3] See Poli 2004 and Albertazzi 2005. Bell 2000 and 2005 provide an intuitionistically-based reconstruction of Brentano's theory. A different interpretation is under elaboration by Herre (in preparation).

Besides anticipation, living systems require the capacity of coordinating (again, intentionally or 'automatically') the rhythm of the system with those of its parts. In this respect, the anticipation of the system as a whole may diverge from those of its parts. Furthermore, living systems are multi-strata systems, composed by different types of components interacting at different levels of organization. Analysis is required of both their material and functional components.

The interaction among the three mentioned topics (anticipation, part-whole structure and levels of organization) provides a cue for better understanding living systems.

5. Ontological and Mathematical Categories

System analysis requires framing ontology in the form of a theory of categories (Poli, 2008). We shall therefore adopt here a categorical viewpoint, meaning that we are looking for "what is universal" (in some domain or in general). In this regard, the most universal feature of reality is that it is temporal, i.e. it changes, and it is subject to countless transformations, movements, alterations. From the point of view of mathematical modelling, the mathematical theory of categories models the *dynamical nature* of reality by resorting to *variable* categories (i.e., toposes). The claim advanced by this paper is that mainstream topos theory suits perfectly the needs of complex systems. However, as soon as one passes from complex systems to super-complex systems, the theory of toposes requires suitable generalizations. Our proposal is then to adopt the framework provided by (a suitably generalized) topos theory for modelling super-complex systems. We have seen that the difference between complex and super-complex systems in based on at least four main issues: levels of reality, chronotopoids, (generalized) interactions, and anticipation. So far, none of them has been adequately formalized. However, considering that chronotopoids and interactions require (and therefore depend on) the theory of levels, and that the issue of anticipation has been advanced by Rosen (1985), subsequent sections will make reference to the issue of levels only. Furthermore, it is apparent that any step towards a proper formalization of the theory of levels (or any other of the mentioned theories) seems to require the development of a non-Abelian framework. Whatever other mathematical property will be required, the first mandatory move is therefore to pass from an Abelian, or commutative, framework (Eilenberg and Mac Lane, 1942,1945; Grothendieck, 1971; Freyd, 1964; Mitchell, 1968; Ehresmann, 1959, 1965, 1966, 2005; Gabriel, 1962; Popescu, 1973) to a non-Abelian one. This key mathematical property of commutativity also includes the mirror-like symmetry $x * y = y * x$; when x and y are operators and the '$*$' represents the operator multiplication.

6. Living Systems Represented as Variable Categories and Universal Colimits. The Underlying Many-Valued LM-logic Algebraic Category

One of the major road blocks to a successful dynamical theory of complex systems, and also of developmental, living systems, has been the lack of a flexible mathematical structure which could represent the immensely variable and heterogeneous classes of biological and social organisms. In the following subsection we propose to re-examine the representation of living systems in terms of such flexible mathematical structures that can vary in time and/or space, thus providing a natural framework for relational/theoretical biology, psychology, sociology or global theoretical constructs addressing environmental problems.

We have already mentioned that the problem of time, i.e. the problem of *the dynamical nature of reality*, is the main problem underling the philosophical theory of categories (see also Poli, 2008). This same problem has also been at the centre of the mathematical theory of categories over the last six decades, and found a first outcome in the idea of *variable category* (be it in the form of variable sets, variable classes, etc). Furthermore, dealing with varying, or variable, objects such as those formalized as variable sets, variable classes, etc. lead to a further generalization of this categorical approach that is founded in Logic, be it Boolean (as in the Category of Sets), Heyting-intuitionistic (as in ‘standard’ Topos theory; Moerdijk and MacLane, 1994; Mac Lane , 2000), or Many-Valued (MV or Lukasiewicz-Moisil (Georgescu, 2006), as in the new generalized version of Topos theory (Baianu, Brown, Glazebrook and Georgescu, 2005, 2006). It is worth mentioning that some of the occasional pitfalls of the categorical approach in specific, logical or mathematical, contexts, as for in example in certain areas of Algebraic Topology or Algebraic Logic, were recognized early by topologists, who also branded this approach as “*abstract nonsense”* even though it continued to facilitate and be widely employed in the proof of general theorems. Their objection lies in the fact that the “universal” may, and does, have a few specific exceptions and counter-examples as one might of course expect it. Things that may appear to be *globally* “the same”, or “categorically equivalent”, may still differ quite significantly in their specific, *local* contexts.

7. Dynamic Equivalence, Analogous Systems and Similarity. Adjointness and Conjugacy

A scientific and/or engineering strategy for dealing with complex systems has long been the analysis of simpler, more readily accessible ‘*models*’ of a complex system. One often attempts to arrive at *computable* models with similar dynamic behavior(s) to that of the original, complex system. Computability of such simple models may often involve the use of a super-fast digital computer, and the models can be made indefinitely more and more complicated through iterated attempts at improved computer simulation.

A formal, categorical approach to analogous systems and dynamic equivalence of systems was first reported by Rosen (1968) from a classical standpoint that is, excluding quantum dynamics; subsequently his approach was extended to the development of biological systems and embryology by means of *adjoint functor* pairs and weak (epimorphic) adjointness (Baianu and Scripcariu, 1973).

Returning now to the issue of computer simulation, one finds upon careful consideration that there is no recursively computable (either simple or complicated) model of both super-complex biological systems and simpler ‘chaotic’ systems (see for example, Baianu, 1987a,b, and the relevant references cited therein). Therefore, complex systems biology cannot be reduced to any finite number of simple(r) mechanistic models that are recursively computable, or accessible to digital computation or numerical simulation. This basic result does not seem, however, to deter the computationally-oriented scientists from publishing a rapidly increasing number of reports on computer simulation of complex biological systems. There is surprising enthusiasm and optimism, not to mention popularity, funding, etc., for computer simulations in both biology and medicine. Heuristic results are both attractive and stimulating, culminating with the aroused expectation of ‘final answers’ to either biological or medical problems by means of digital super-computers. It seems, however, that super-computers are no match for super-complexity, or even for the simpler, ‘chaotic’ dynamics, a result also widely recognized by many chaotic dynamic theorists.

Fundamentally, the limitations of digital computers that rely upon recursive computations are traced back to the Boolean (or Chrysippian) logic underlying the design of all existing digital computers, and also to the Axiom of Choice upon which set theory is based (Moerdijk and MacLane, 2004). On the other hand, biological, super-complex system dynamics is governed by a many-valued (MV) logic characteristic of biological processes including genetic ones (Baianu, 1977, Baianu et al, 2006). Such an MV-logic is both *non-commutative* (unlike the Boolean or the Heyting-intuitionistic logic of standard Toposes) and *irreducible* to Boolean or intuitionistic logics (of course, with the exception of the special cases of the category of *centred* Lukasiewicz-Moisil logic algebras that can be mapped isomorphically onto Boolean Logic algebras (Georgescu and Vraciu, 1970; Georgescu, 2006). Unlike the well known result of von Neumann's for the *Universal Automaton,* super-complex biological systems are *not* recursively, or numerically, computable.

Although this limits severely the usefulness of all digital computers in complex systems biology and mathematical medicine, it does not render them useless for experimentation, data collection and analysis or graphics and graphical presentation/representation of numerical results. The limitations come in the final analysis where computer simulations of super-complex system dynamics may not claim a full, or complete, dynamical modelling of living systems as such a result has been formally proven to be unobtainable, in general, through recursive computation with algorithms, universal Turing machines, etc. (Baianu, 1986; Rosen, 1987). Furthermore, it may be possible to extend the recursive concept of numerical analogy to one of symbolic computation through *conjugacy* of dynamic state spaces (Baianu et al, 2007c) and similarity of the corresponding systems, as in the case of adjoint dynamical systems (Baianu and Scripcariu, 1973; Baianu, 1987a,b). Thus, non-recursive *algebraic-topological computation* is still possible, of course, for living systems and their essential subsystems, such as genetic networks, by employing *non-commutative, irreducible MV*-logics, either in a general context (Georgescu, 2006) or in more specific contexts, such as the controlled dynamics of genetic networks in biological organisms (Baianu, 1977, 2004a,b, 2005a,b; Baianu et al, 2006 a, b). Non-commutative super-complex dynamic modelling has just begun in biology and medicine, including diagnostics. *Biostatistics* based on such MV-logics has also just become a possibility (Georgescu, 2006). The latter developments are also suggesting a *paradigm shift* occurring now in system theory – from Abelian to non-Abelian theories. This new paradigm has perhaps already began with the earlier introduction of *non-commutative* geometric spaces obtained through deformation as models of Quantum Spaces in attempts at formalizing quantum gravity by A. Connes (1994, and references cited therein).

8. Towards a Non-Abelian Systems Theory

One could formalize the hierarchy of multiple-level relations and structures that are present in super-complex systems in terms of the mathematical Theory of Categories, Functors and Natural Transformations (TC-FNT). On the first level of such a hierarchy are the links between the system components (or "*objects")* represented as *morphisms* of a structured category which are subject to the ETAC axioms/restrictions of Category Theory (Lawvere, 1966). Then, on the next, second level of such a categorical hierarchy one considers *functors,* or links, between the first level categories which compare two categories by associating objects from the first category to objects in the second category, and morphisms of the first category to morphisms of the second one. On the third level, one compares, or links, such functors using *natural transformations* in a 2-category (or *meta*-category) of categories. At this level, natural transformations not only compare functors but also involve mappings that associate elements of the first level objects (system components) thus 'closing' the structure and establishing 'the universal links' between items as an integration of both first and second level links between items. The advantages of this constructive approach in the mathematical theory of categories, functors and natural transformations have been recognized since the beginnings of this mathematical theory in the seminal paper of Mac Lane and Eilenberg (1945). A relevant example from the natural sciences, e.g., neurosciences, would be the *higher-dimensional algebra of processes* of cognitive processes of still more, linked sub processes (Brown, 2004). Yet another example would be that of groups of groups of item subgroups, 2-groupoids, or double groupoids of groups of items. The hierarchy constructed above, up to level 3, can be further extended to higher, n-levels, always in a consistent, natural manner. This type of global, natural hierarchy of items inspired by the mathematical TC-FNT has a kind of *internal symmetry* because *at all levels*, the link compositions are natural, that is the all link compositions that exist are *transitive*, i.e., $x < y$ and $y < z \Rightarrow x < z$, or $f: x \rightarrow y$ and $g: y \rightarrow z \Rightarrow h: x \rightarrow z$, and also $h = g * f$. The general property of such link composition chains or diagrams involving any number of sequential links is called *commutativity*, or the naturality condition; this key mathematical property also includes the mirror-like symmetry $x * y = y * x$; when x and y are operators and the star, '$*$', representing an operator multiplication. Then, the equality of $x * y$ with $y * x$ implies that the x and y operators '*commute';* in the case of an eigenvalue problem involving such commuting operators, the two operators would share the same system of eigenvalues, thus leading to 'equivalent' numerical results. This is very convenient for both mathematical and physical applications (such as those encountered in quantum mechanics). Unfortunately, not all operators 'commute', and not all mathematical structures are commutative. A structure is called 'Abelian' if it commutes everywhere the composition '$*$' is defined. Thus, as a prominent example a commutative group is Abelian. The more general case is however the *non-Abelian* one; any structure that is not commutative everywhere, that is globally, is thus non-Abelian. A general example is that of the categories defined above; only a sub-class of such categories are Abelian. Another example is that of a non-commutative structure relevant to Quantum Theory – the Clifford algebra of quantum observable operators (Dirac, 1962); yet another, more recent and popular, example is that of *C*--algebras* of (quantum) Hilbert spaces; such structures, are of course also non-Abelian, with *non--Abelianness* being the weaker condition than *global* non-commutativity. Last but-not least, are the interesting mathematical constructions of non-commutative 'geometric spaces' obtained by 'deformation' introduced by Allan Connes (1994) as possible models for the physical, quantum space-time; such non-commutative 'geometric spaces' are therefore also non-Abelian, as is also their category which is only locally, but not globally, commutative. Thus, not all diagrams of non-commutative 'geometric spaces' and connecting homeomorphisms are commutative. However, it was shown that the property of *Abelianness* can be extended in the case of categories to a subclass of categories that satisfy six additional axioms Ab1 to Ab3 and their duals, Ab1* to Ab3* (Freyd, 1964). Such Abelian categories have formally identical *meta*-theorems to those exhibited by the (Abelian) category ***G*** of commutative groups; therefore, one has ***G*** as the best mathematical model for any Abelian category (p. 2 of Popescu, 1973).

Because, as explained above, both the (Clifford) algebra of quantum observable operators and the related *C*-algebras* of (quantum) Hilbert spaces are *non-commutative* structures, the microscopic, or quantum, fundamental (sub)levels of physical reality *do not satisfy the Ab-axioms*, or conditions for Abelianness, in TC-FNT – the 'standard' mathematical theory of categories (functors and natural transformations). Therefore, quantum theory itself is *not Abelian*, and it thus follows that a General Categorical Ontology which considers all items, from all levels of reality—including those on the 'first', *quantum* level (that are not commutative) – must also be *non-Abelian* on account of the fundamental quantum sublevels that are not commutative.

Moreover, mathematical, *Non-Abelian* Algebraic Topology (Brown, Higgins and Sivera, 2007b), as well as the non-Abelian Quantum Algebraic Topology (NA-QAT; Baianu et al., 2005), and the physical, Non-Abelian Gauge theories may provide all the ingredients needed for a proper foundation of novel/ non-Abelian, hierarchical multi-level theories of super-complex system dynamics. Furthermore, it was recently pointed out by Baianu et al (2005, 2006a,b; 2007a; 2008) that the current and future development of both NA-QAT and of a quantum-based Complex Systems Biology involve *a fortiori* non-commutative, many-valued logics of quantum events, such as the Lukasiewicz-Moisil (LMV) logic algebra (Georgescu, 2006; Georgescu and Vraciu, 1970), complete with a fully-developed, novel probability measure theory grounded in the LMV-logic algebra (Georgescu, 2006). The latter paves the way to a new projection operator theory founded upon the (non-commutative) quantum logic of events, or dynamic processes, thus opening the possibility of a complete, non-Abelian Quantum theory. Finally, such recent developments point towards a *paradigm shift* in systems theory and to its extension to more general, Non-Abelian theories, well beyond the bounds of commutative structures/spaces and also free from the restrictions and limitations imposed by the Axiom of Choice to Set Theory.

9. Conclusions

By way of a conclusive synthetic summary, it is worth underlining that the proposal of higher-order complex systems crucially depends on two different and so far only partially overlapping threads. From one side, we have the ontological thread comprising levels of reality, chronotopoids, generalized interactions and anticipation. On the other side, several distinct mathematical frameworks *are* actually under active development, and are also gaining momentum. These include, but are not limited to, categories of Lukasiewicz-Moisil algebras, variable biogroupoids, and variable topologies. All of them are part and parcel of a wider movement towards substantially more general mathematical structures usually termed non-Abelian mathematics that may also include non-commutative structures. The former have been originally developed in the effort of understanding at high energy quantum physics, and are also promising candidates for addressing biological, psychological and social phenomena. Abelian structures, on the other hand, are patently far too rigid and/or too ‘symmetric’ for smoothly modelling dynamic phenomena/processes as variable, rich and (super)-complex as those pertaining to life, mind and society. So far, the overlapping and mutual breeding between the ontological and the mathematical threads is still limited, even though a definite trend to bridge the gaps between philosophy and mathematics is already established; see for example the website and the current sections in the Stanford Encyclopedia and references on Category Theory and Philosophy of Mathematics/Science. Major efforts are thus channelled now into categorical logics and categorical frameworks for computer science/symbolic programming (Baianu, 1971b), as well as the categorical foundations of mathematics (Lawvere, 1966) and ontology/philosophy (Brown et al., 2007a). Further developments of universal and categorical ontology in higher dimensional algebras are also being considered (Brown et al., 2007a, b; Baianu et al., 2007a--c). Some logicians have also made already the advance towards category theory and non-Abelian structures, as in the case of Q-logic (Dalla Chiara et al., 2004). Although many philosophers are not yet sufficiently familiar with the rather advanced mathematical subjects mentioned here, and many mathematicians are not yet sufficiently aware of all subtleties and difficulties posed by ontology, the trend seems to be already established towards *non-Abelian* theories in physics, mathematics, logics, ontology, and perhaps also more generally in the philosophy of science and metaphysics. However, something even deeper, and potentially far more important than the above, is ongoing here. Both the new ‘anti-fundamentalist’ ontology and the non-Abelian mathematics discussed in our essay are presently not recognized to be in the mainstream philosophy or mathematics. Apparently, many philosophers and mathematicians are unwilling to embark towards such highly uncharted territories. However, the world is so complex and so widely differentiated – even though it is ultimately and intimately unified – that one cannot hope to solve most of the demanding real-world problems without both flexible enough mathematical structures and a deeper understanding of their ontological, multi-stratified and many-layered attributes than it has been presumed before.

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